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EVIDENCE FOR THE MELT-LUBRICATION OF PROJECTILE BANDS

R. S. MONTGOMERY

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
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WATERVLIET N.Y. 12189

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Despite the long-time acceptance of melt-lubrication of rotating bands by the Army ~~S~~cientific community, all of the evidence supporting this conclusion has not been collected and, indeed, some has never been published. The melt-lubrication of rotating bands is very important because the~~n~~ sliding is lubricated and friction and wear ~~is~~ are determined only by the characteristics of the molten film and the amount of melting at the sliding interface. Melt-

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20. ABSTRACT (CONT'D)

lubrication results in much less resistance and much less severe wear than would otherwise be the case. Friction, wear and metallographic evidence from examination of recovered projectiles and fired cannon tubes show the melt-lubrication of projectiles sliding on a gun bore. This melt-lubrication is caused by the production of a thin surface film of molten rotating band material. Such a molten surface layer can also be produced on the surface of materials other than copper alloys contacting the bore at high bearing loads.

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The metallography in this report was by Mrs. Theresa Brassard.

INTRODUCTION

The fact that a thin molten film is produced on the surface of rotating bands after only a short distance of sliding down a gun tube was well-accepted by researchers at least as far back as World War II.[1,2] It was well-known that the coefficient of friction rapidly decreased as would be expected with the establishment of melt-lubrication. The theory of heating of rotating bands indicated that melting of the band surface occurs in many guns;[3] this was confirmed by the known facts of coppering of the bore surface[4] and by direct measurements of the interface temperature.[5] In addition, copper had been observed to have dripped out of the muzzle end of a caliber .50 machine gun barrel during ~~the~~ a severe firing schedule.[4]

Since that time, the idea of melt-lubricated sliding of projectiles has been further corroborated.[6] Herzfeld and Kosson published a report in 1953 where they postulated the melting of rotating band material at the band-tube

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[1]William S. Benedict, "Bore Friction," Hypervelocity Guns and the Control of Gun Erosion, Summary Tech. Rep. of NRDC Division 1, Office of Scientific Research and Development, Washington, D.C.

[2]R. Beeuwkes, Jr., "Band Pressure in Design," Watertown Arsenal, WAL 730/217, August 1944.

[3]C. L. Critchfield, "On the Heating of Rotating Bands," OSRD 3329, Report No. A-256, Geophysical Lab, CIW, February 1944.

[4]Lloyd E. Line, Jr., "Description of Eroded Gun Bores," Hypervelocity Guns and the Control of Gun Erosion, Summary Tech. Rep. of NRDC Division 1, Office of Scientific Research and Development, Washington, D.C., 1946.

[5]E. L. Armi, J. L. Johnson, R. C. Machler, and N. E. Polster, "Measurement of Frictional Heat Input in Gun Barrels and Frictional Bullet-Bore Interface Temperatures," OSRD 6471, Report No. A-400, Leeds & Northrup Co., September 27, 1945.

[6]Anon., "Copper Loss From Driving Bands at High Velocities," ARE, Woolrich Arsenal, Ballistics Branch Memo No. 3, September 1949.

interface immediately after shot start.[7] The force of resistance, the work done against resistance, and the loss of band material were predicted on this basis for several firings and the predictions compared with experiment. The agreement with the experiment was quite adequate in most cases. Montgomery published two papers in 1976[8,9] where he reported experimental friction measurements from 155 mm howitzer firings and pointed out that these were consistent with melt-lubrication and offered an explanation of why the coefficients of friction for actual projectiles sliding down gun tubes were much lower than were coefficients measured in the laboratory using a pin-on-disk apparatus. Earlier Montgomery had published the results of the pin-on-disk experiments conducted by the Franklin Institute from 1946 to 1956 under contract to the U.S. Army.[10] While coefficients of friction were significantly higher than was the case with actual projectiles, it was shown that wear rate was a function of melting point of the slider material which would indicate that the wear mechanism at high sliding speeds was melting. Montgomery also reported that the coefficients of friction for gilding metal sliding on steel and on chromium plate are identical for velocities of 300 ft/s and higher although they are different below this velocity.[11] This would

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[7]C. M. Herzfeld and R. L. Kosson, "A Theory of Bore Friction," BRL Report No. 851, March 1953.

[8]R. S. Montgomery, "Surface Melting of Rotating Bands," Wear 38, p. 235 (1976).

[9]R. S. Montgomery, "Projectile Lubrication by Melting Rotating Bands," Wear 39, p. 181 (1976).

[10]R. S. Montgomery, "Friction of Gilding Metal Sliding on Chromium-Plated Steel," Wear 36, p. 275 (1976).

[11]R. S. Montgomery, "Friction of Gilding Metal Sliding on Chromium-Plated Steel," Wear 50, p. 387 (1978).

be predicted if the sliding at high velocities was melt lubricated. Recen C. M. McC. Ettles has developed a closed form analytical solution for melt lubrication that quantifies the pin and disk results and the results obtained with guns.[12]

Despite the general acceptance of melt-lubrication of rotating bands, all of the evidence supporting this conclusion has not been collected and, indeed, some has never been published. The melt-lubrication of rotating bands is very important because then sliding is lubricated and friction and wear are determined only by the characteristics of the molten film and the amount of melting at the sliding interface.

DISCUSSION

Friction and Wear Evidence

When the coefficients of friction for projectiles with gilding metal rotating bands fired in 155 mm howitzers (with steel bores) are plotted as functions of projectile travel, it can be seen that the initial friction is very high but that it rapidly drops to about 0.1 by the time the bands are completely engraved (see Figure 1). The steady state coefficient of friction, which appears to be about 0.02, is reached after only about 5 inches of travel. This means that the mechanism of sliding changes drastically after only a few inches of movement. It is probable that this is caused by melting of rotating band surface and the establishment of melt lubrication.

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[12]C. M. McC. Ettles, Private Communication, September 1982.

An extensive laboratory study at the Franklin Institute was supported by the U.S. Army from 1946 to 1956 and a great deal of data was collected at sliding speeds up to 1800 ft/s using a sophisticated high-speed pin-on-disk apparatus.[10] The apparatus is shown in Figure 2. Friction and wear of pins of gilding metal, copper, and projectile steel and the friction of annealed iron all sliding on gun steel were extensively investigated. In addition, there were a few experiments with pins of other materials. The data for copper sliding on gun steel is typical of the results that were obtained. At low pressure-velocity values both friction and wear rates were very high and irregular and were not functions of this product. At the higher sliding velocities and bearing pressures, the coefficient of friction decreased to a more or less constant value and the wear rate became a smooth function of PV (see Figures 3 and 4). The product PV determines the rate of heat generated at the sliding interface (at constant coefficient of friction). The sliding behavior of copper on steel is clarified by plotting friction and wear rates as functions of the rate of heat generated (see Figures 5 and 6). It is apparent that both friction and wear rates are not functions of this rate of heat generated at low bearing pressures and sliding velocities. However, at the higher rates of heat generation, friction is almost constant and wear rate is proportional to the square of the rate of heat generation. This indicates melting of the rotating band surface and establishment of melt-lubrication.

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[10]R. S. Montgomery, "Friction of Gilding Metal Sliding on Chromium-Plated Steel," Wear 50, p. 387 (1978).

With melt-lubrication, the wear rate should be a function of the amount of melting. If the linear wear rates of the different materials sliding on gun steel at the same rate of heat generation are plotted as functions of the reciprocal of their absolute melting points, a straight line on semi-logarithmic graph paper results with the lower melting materials wearing considerably faster than the higher (see Figure 7). The two materials which fall conspicuously below the line are copper and aluminum, the materials with the highest thermal conductivities. Evidently, a high thermal conductivity results in the material acting as if it had a higher melting point than it actually has owing to the rapid conduction of heat away from its surface.

An apparent anomaly in the laboratory work is that the values of the coefficient of friction are many times more than those actually observed in a gun tube. While the environment in a gun tube is considerably different from the laboratory conditions, the exact reasons for the disparity were not clear until the publication of a theoretical study on lubrication by a melting solid.[13] From this analysis, the coefficient of friction is proportional to the square root of the non-dimensional sliding speed, S. This speed is defined as

$$S \equiv \mu U/xL$$

where μ is the liquid viscosity, U the sliding velocity, x the length of the slider, and L the volumetric heat of melting. Therefore, the coefficient of friction is inversely proportional to the square root of the length of the

[13] W. R. D. Wilson, "Lubrication by a Melting Solid," Trans. ASME, Ser. F, 98, (1) p. 2 (1976).

slider for any particular sliding velocity. Since the length of an actual rotating band is many times greater than the length of a test pin, this could account for at least a portion of the disparity in the coefficients. In this study it was also shown that, in the case of a melting slider, the system is not self-sustaining until very high values of non-dimensional bearing pressure are reached. That is, below these values of bearing pressure the leading edge of the slider is not lubricated by the liquid metal and consequently the coefficient of friction is much greater. The higher coefficients of friction measured in the laboratory pin-on-disk experiments could easily be accounted for by the small slider size and the relatively low bearing pressures.[9]

For melt-lubrication, just as any liquid lubrication, the coefficient of friction is dependent on the thickness and viscosity of the liquid film and independent of the materials of the sliding members. This was found to be the case in the pin-and-disk experiments at high sliding speed. It was found that the coefficients of friction for gilding metal sliding on both gun steel and on chromium plate are identical for velocities of 300 ft/s and higher although they are different below this velocity.[11]

Ettles has been able to develop a new and different melt-lubrication analysis which adequately explains both the laboratory pin-on-disk results and the results observed with an actual cannon.[12] His innovation is the conjecture that at lower velocities and bearing pressures and consequently lower

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[9] R. S. Montgomery, "Projectile Lubrication by Melting Rotating Bands," Wear 39, p. 181 (1976).

[11] R. S. Montgomery, "Friction of Gilding Metal Sliding on Chromium-Plated Steel," Wear 50, p. 387 (1978).

melting rates, the molten film under the front portion of the slider is striated as in "starved" oil film bearings. Even at higher velocities and bearing pressures he finds that the coefficients of friction are two orders of magnitudes higher than "normal" oil film hydrodynamics because the greater part of the film is striated, which contributes to friction but not load support.

Metallographic Evidence

There is also metallographic evidence to support the idea of melt-lubrication of projectiles sliding down gun tubes. Many fired cannon tubes and recovered projectile have been examined and the sum total of the evidence is very compelling although alternate explanations can be devised in some of the individual cases.

Surface cracks on the bores of cannon firing copper and gilding metal banded projectiles are normally filled with copper or copper alloy which evidently entered the crack as a liquid. The presence of copper alloy in the cracks in a chromium-plated bore has even been suggested as an important force tending to cause spalling of the plate. The presence of copper alloy in surface cracks is illustrated in Figure 8. This is a photomicrograph of a section of an unplated steel 155 mm M199 howitzer tube after extensive firing.

The bands on recovered projectiles with copper or gilding metal rotating bands often show a surface layer which had been molten at one time. Probably because recovered projectiles have often been subjected to considerable abrasion during the recovery process, this previously molten film is not found

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[12] C. M. McC. Ettles, Private Communication, September 1982.

in all cases. The film is illustrated in Figure 9. This is photomicrograph of a section through the band of an 8 inch M650 projectile recovered at Yuma Proving Ground. In this case, the band is of copper. To be certain about the character of the surface film, this rotating band was also examined using a scanning electron microscope (see Figure 10). It is difficult to explain this surface structure without concluding that the surface had been molten at one time.

Surface melting of another relatively low-melting metal is shown by recovered fragments of the sabot of a 105 mm M392A2 APDS tank gun projectile (see Figure 11). The "petals" of this sabot are made of AZ61A magnesium alloy which contains 6.01 percent aluminum and 1.20 percent zinc. These petals frequently have marks where one side has slid on the rifling and they show the same kind of surface layer shown by copper alloy rotating bands. Therefore this magnesium alloy can also be melt-lubricated if it slides on the bore of a gun.

At some point as the melting point increases, a metal will not be melt-lubricated sliding on a cannon bore. Evidently Herzfeld and Kosson[7] felt that iron would not be melt-lubricated because they predicted large resistances and extremely severe tube wear with iron rotating bands. We now know that this is not the case and that iron rotating bands are melt-lubricated just as are copper alloy bands. Figure 12 is a photomicrograph of a section of a recovered experimental soft iron band used on a 105 mm M1 howitzer projectile.

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[7]C. M. Herzfeld and R. L. Kosson, "A Theory of Bore Friction," BRL Report No. 851, March 1953.

There is a thin (at least with this specimen) but definite surface layer which had been molten. The examination of the marks on body engraved projectiles should also provide evidence of the melt-lubrication of projectiles with iron bands. Body engraved projectiles have contacted the lands of the rifling near the muzzle at high sliding speeds.[14] Figure 13 is a photomicrograph of a section of a body-engraved 8 inch M106 projectile fired at zone 9 which shows that the surface of the steel does indeed melt. This corroborates the field observation that a purge hole located on a land just one quarter inch forward of the origin-of-rifling of the 152 mm gun firing sintered iron banded projectiles tended to become plugged with molten iron.[15]

CONCLUSION

Friction, wear evidence and metallographic evidence, obtained from examination of recovered projectiles and fired cannon tubes confirm the melt-lubrication of projectiles sliding on a gun bore. This melt-lubrication is caused by the production of a thin surface film of molten rotating band material. Such a molten surface layer can also be produced on the surface of other parts of a projectile contacting the bore at high bearing loads. The significance of individual pieces of evidence can be argued but the sum total of all the evidence is conclusive. Melt-lubrication results in much less resistance and much less severe wear than would otherwise be the case.

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[14] R. S. Montgomery, "Muzzle Wear of Cannon," Wear 33, p. 359 (1975).
[15] A. A. Albright, Personal communication (1975).

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1. William S. Benedict, "Bore Friction," Hypervelocity Guns and the Control of Gun Erosion, Summary Tech. Rep. of NRDC Division 1, Office of Scientific Research and Development, Washington, D.C., 1946.

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6. Anon., "Copper Loss From Driving Bands at High Velocities," ARE, Woolwich Arsenal, Ballistics Branch Memo No. 3, September 1949.

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9. R. S. Montgomery, "Projectile Lubrication by Melting Rotating Bands," Wear 39, p. 181 (1976).

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11. R. S. Montgomery, "Friction of Gilding Metal Sliding on Chromium-Plated Steel," Wear 50, p. 387 (1978).

12. C. M. McC. Ettles, Personal Communication (1982).

13. W. R. D. Wilson, "Lubrication by a Melting Solid," Trans. ASME, Ser. F, 98, (1) p. 22 (1976).

14. R. S. Montgomery, "Muzzle Wear of Cannon," Wear 33, p. 359 (1975).

15. A. A. Albright, Personal Communication (1975).

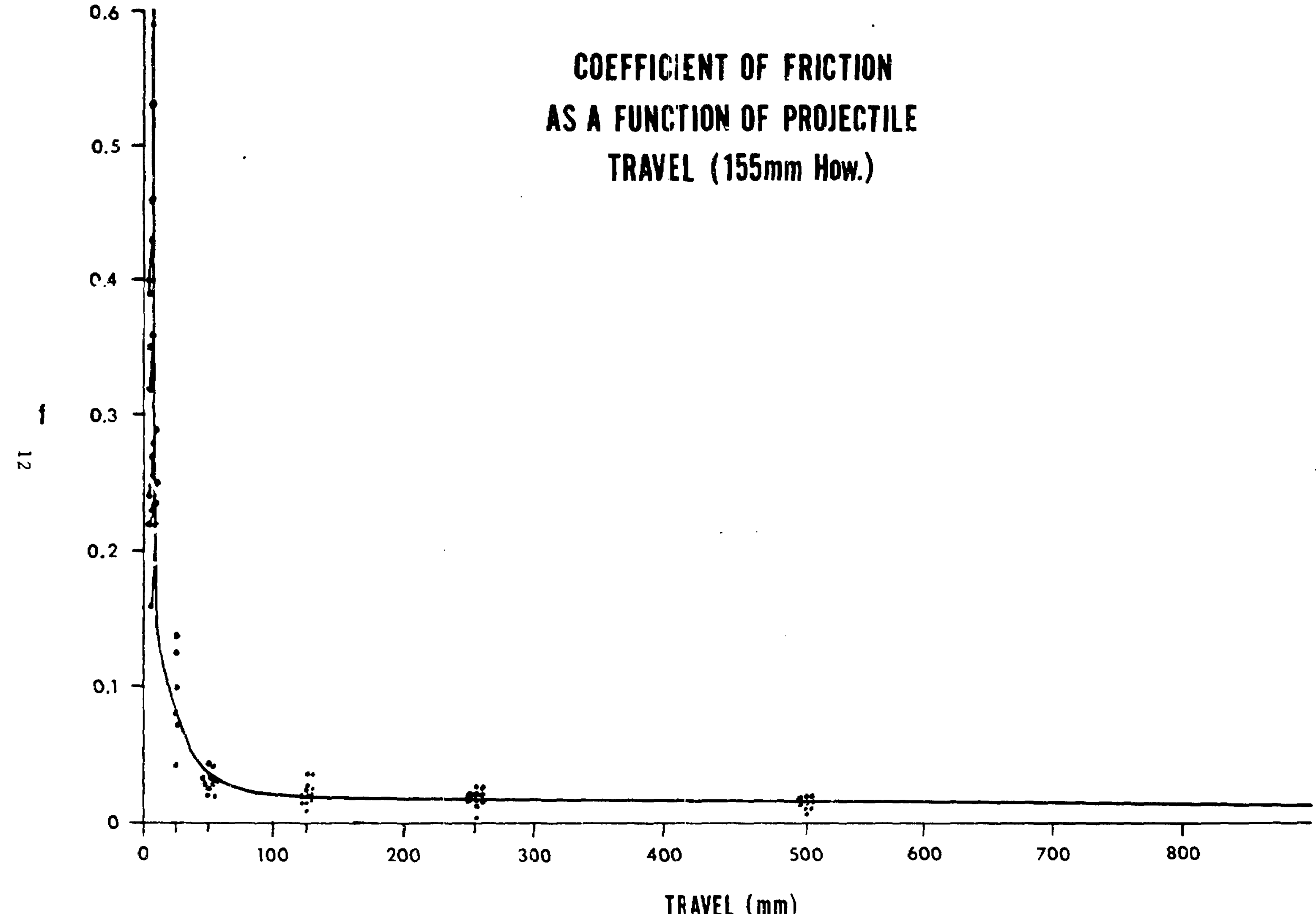


Fig. 1. Coefficient of Friction as a Function of Projectile Travel for Initial Travel of 155mm Howitzer Projectiles (Data from Reference 8).

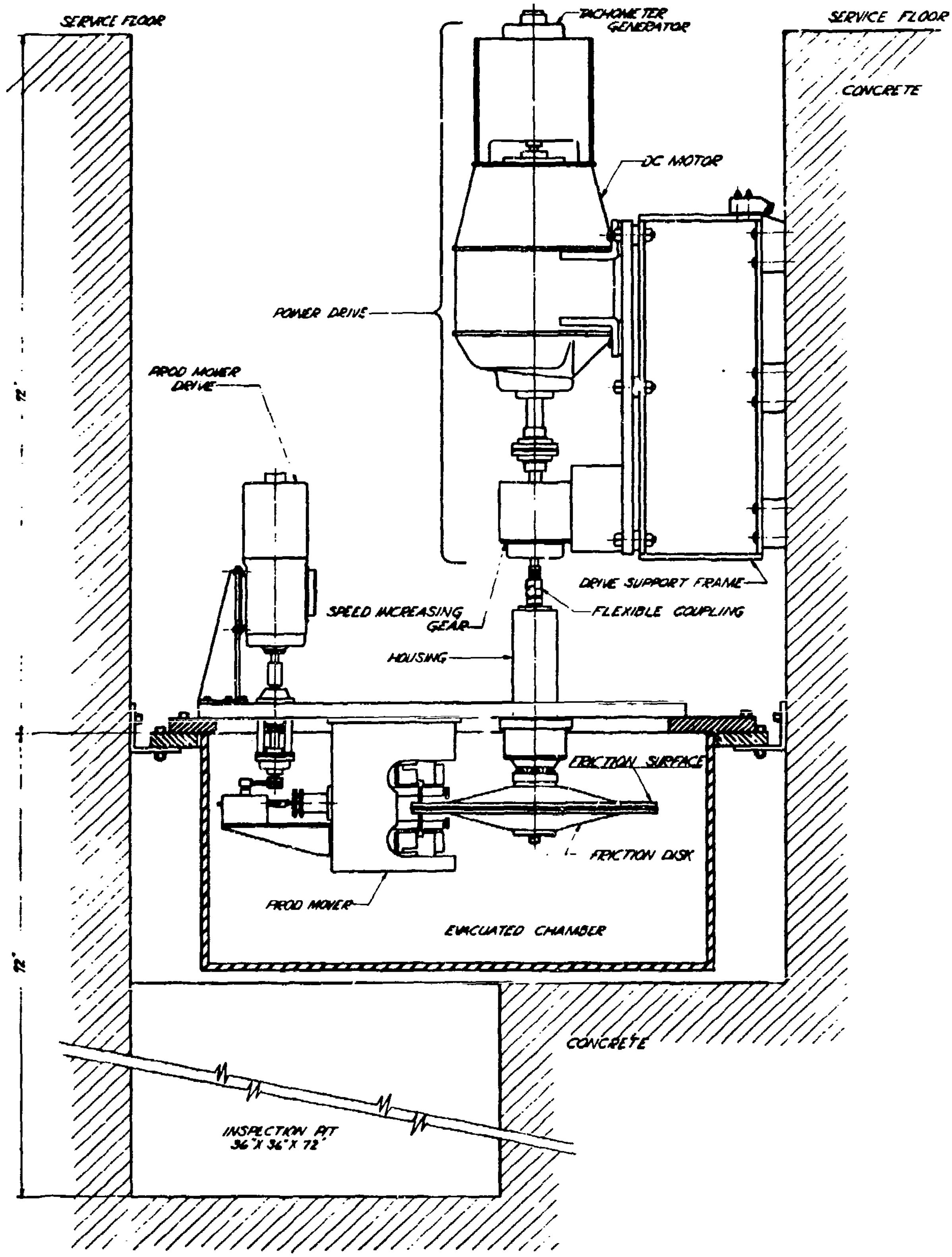


Figure 1.Schematic Assembly of Friction Machine used by Franklin Institute. (From Ref. 10).

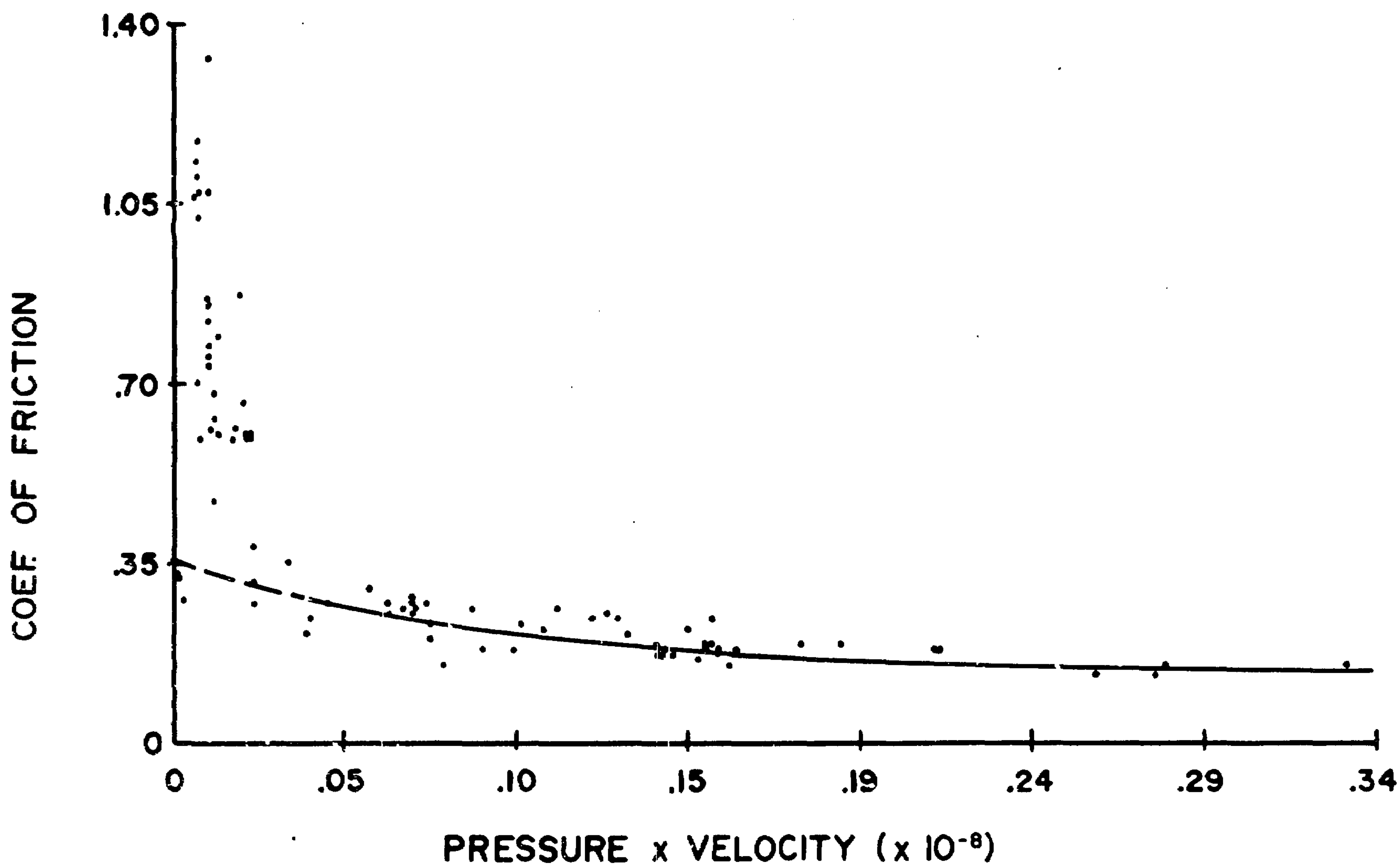
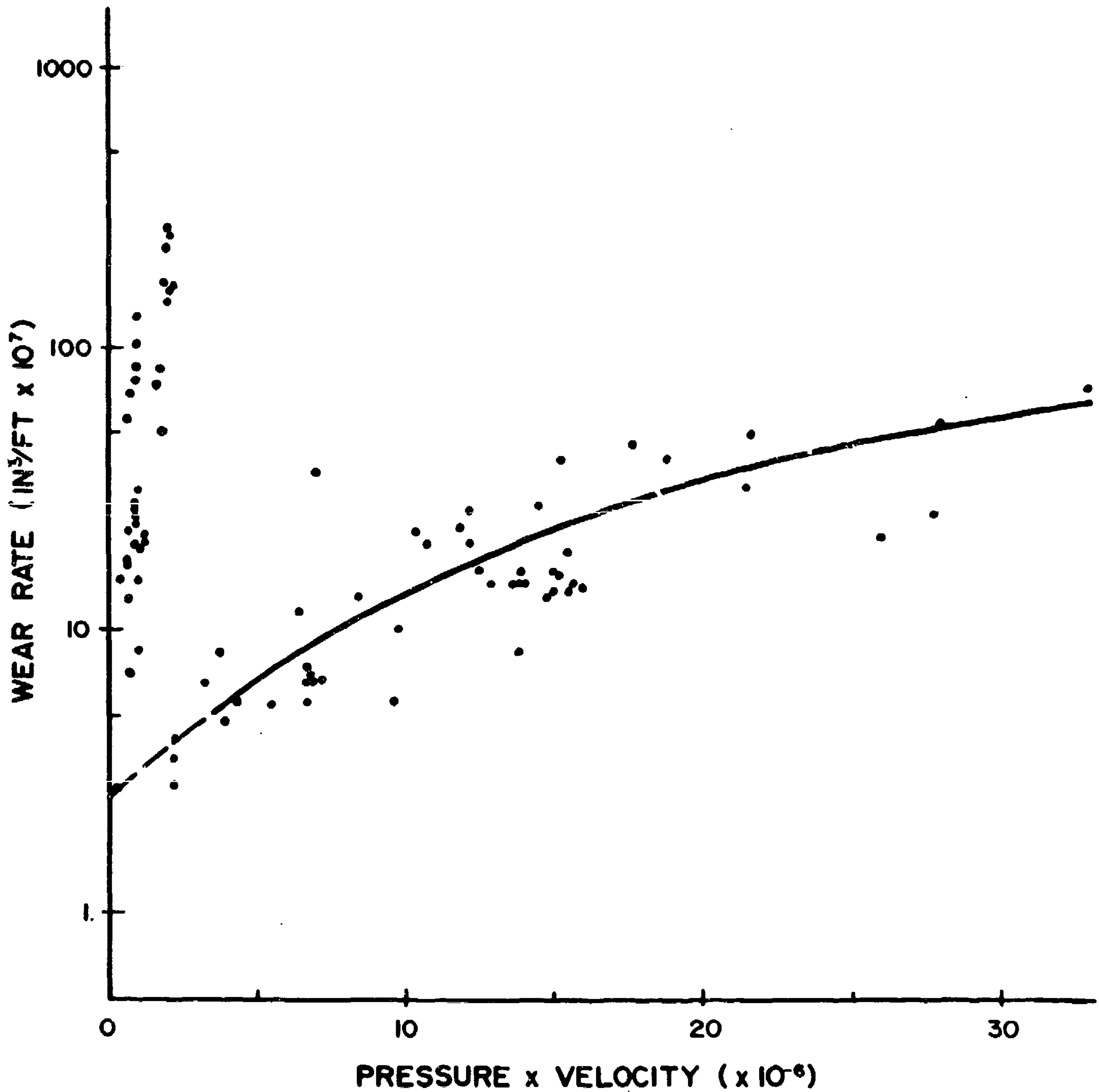


Figure 3. Coefficient of Friction of Copper as a Function of Pressure x Velocity (lb in.$^{-1}$ ft s^{-1}) (from Reference 10).

Figure 4. Wear Rate of Copper as a Function of Pressure x Velocity ($lb\ in.^{-2}\ ft\ s^{-1}$) (from Reference 10).



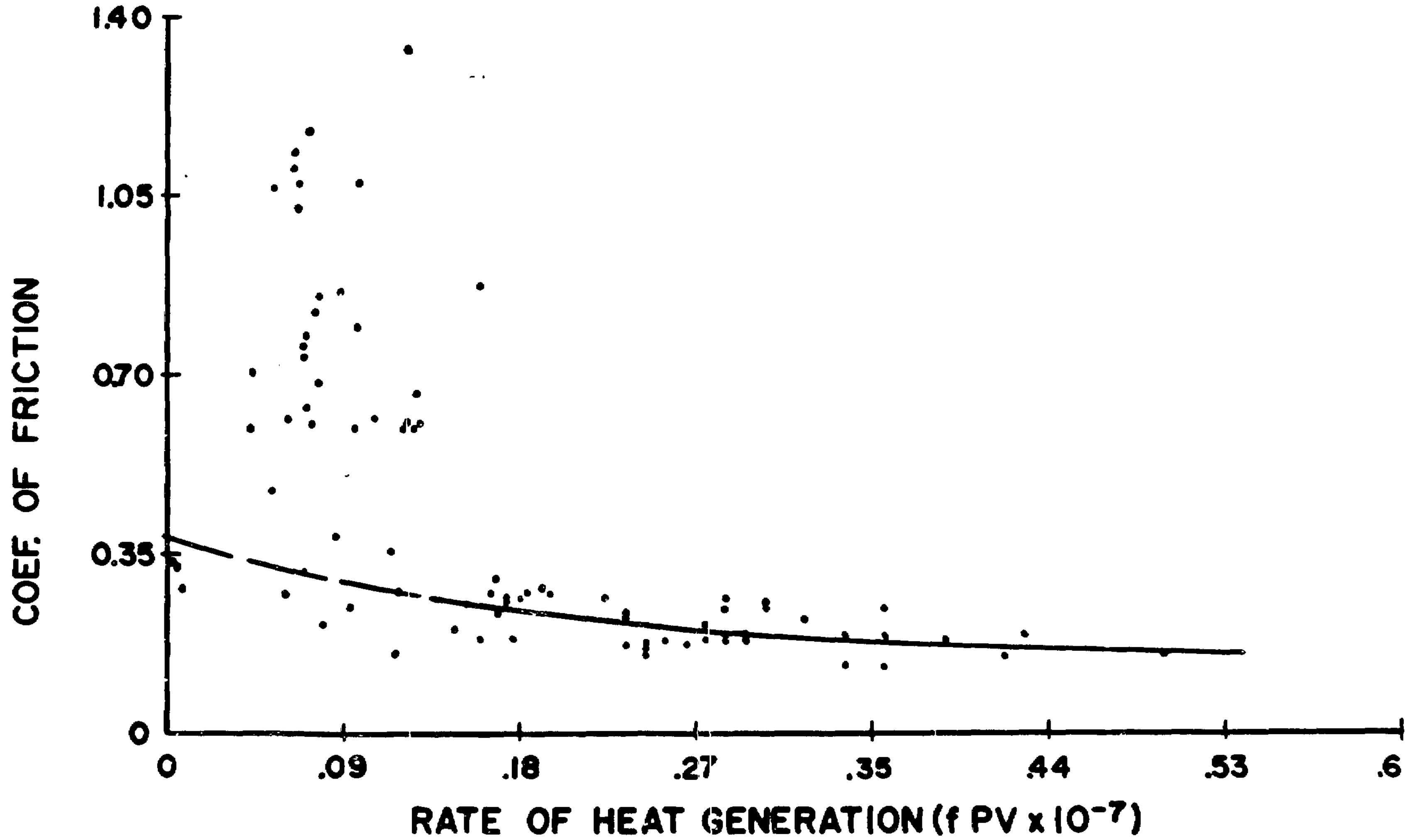


Figure 5. Coefficient of Friction of Copper as a Function of Rate of Heat-Generation (lb. in.$^{-2}$ ft s^{-1}) (from Reference 10).

Figure 6. Wear Rate of Copper as a Function of Rate of Heat-Generation (fPV) (from Reference 10).

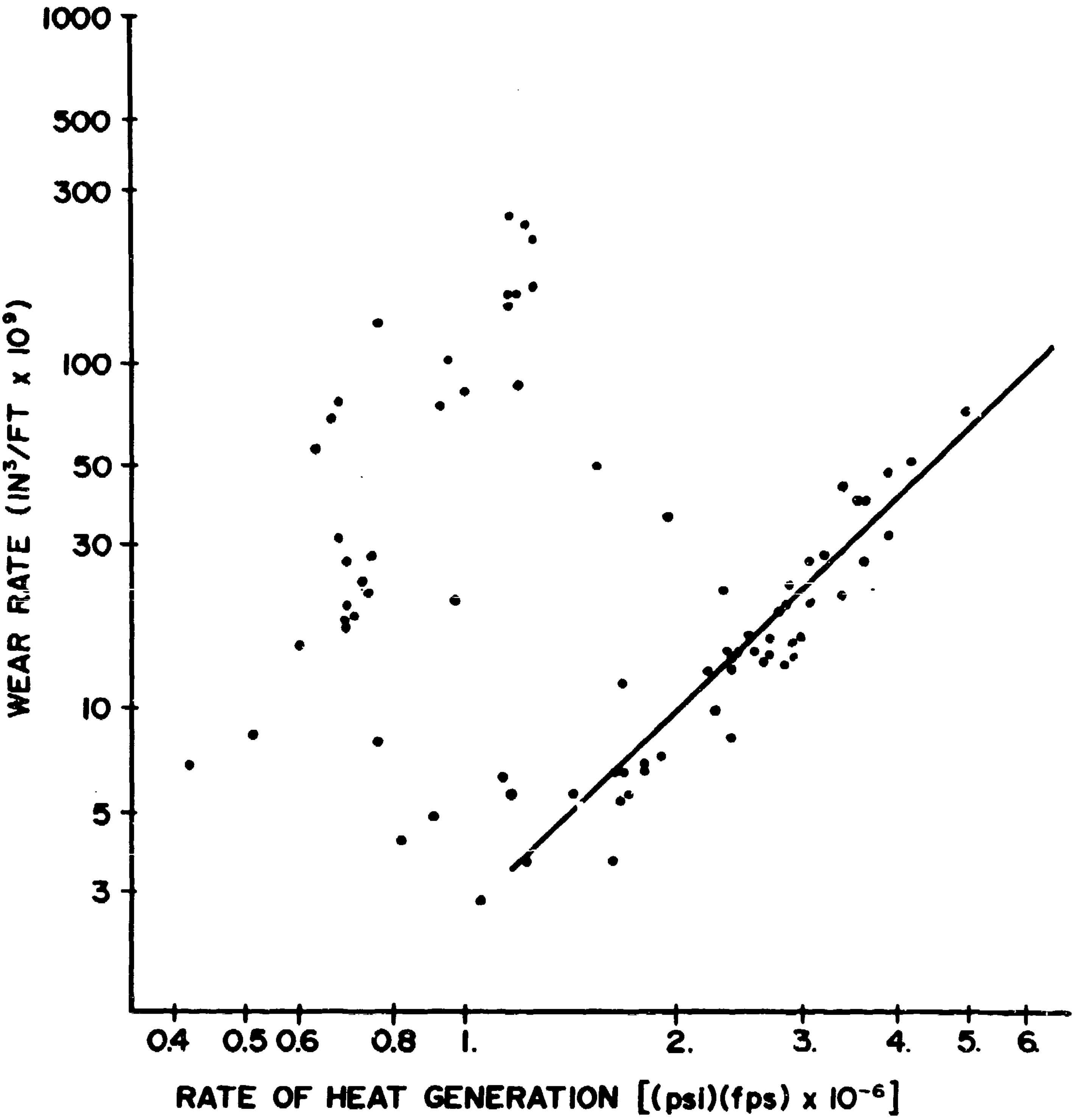
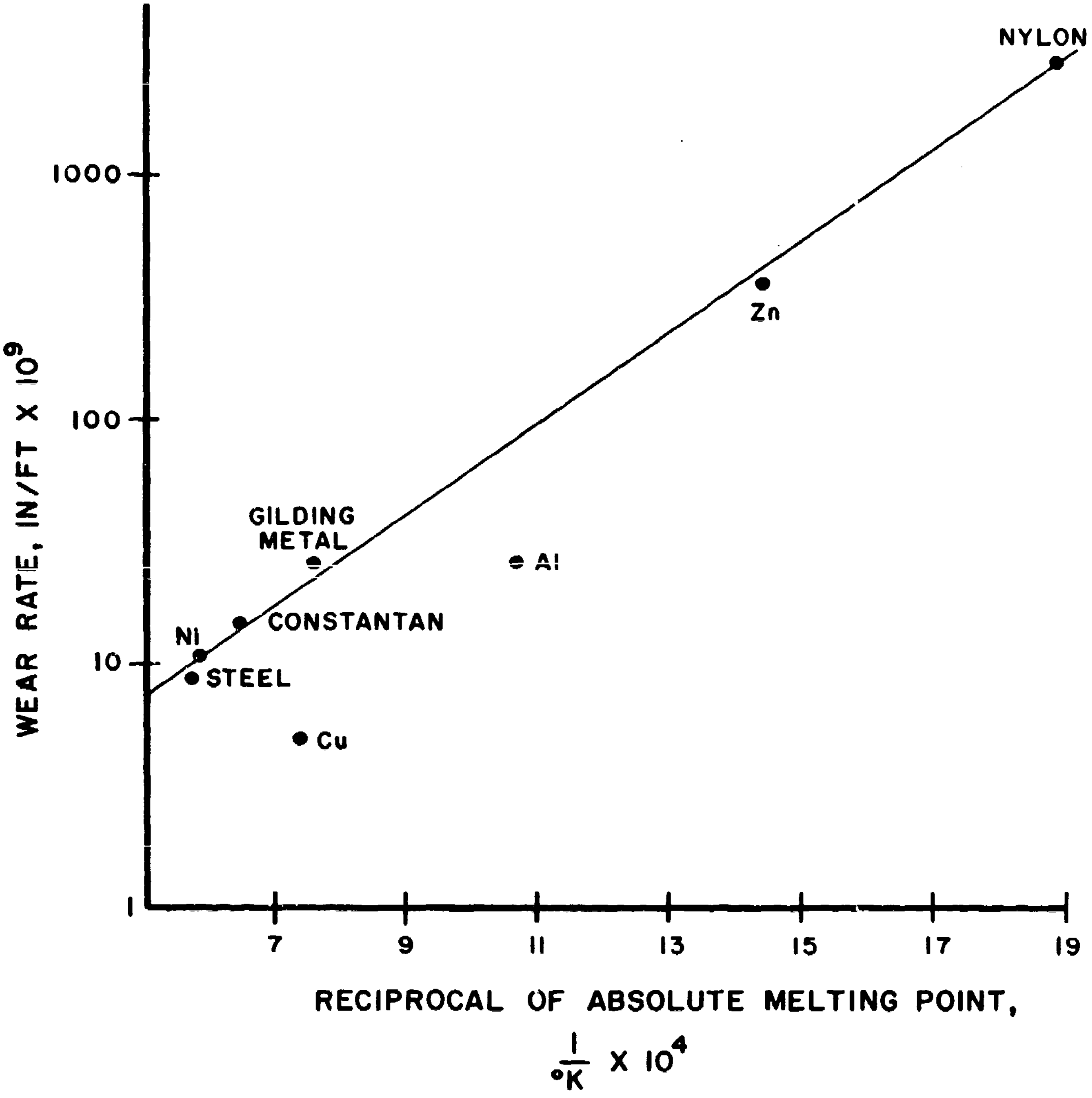


Figure 7. Wear Rates of Different Materials at a Particular Rate of Heat-Generation (fPV = 10^6 lb in.$^{-2}$ ft s^{-1}) as Functions of the Reciprocals of Their Absolute Melting Points (data from Reference 10).



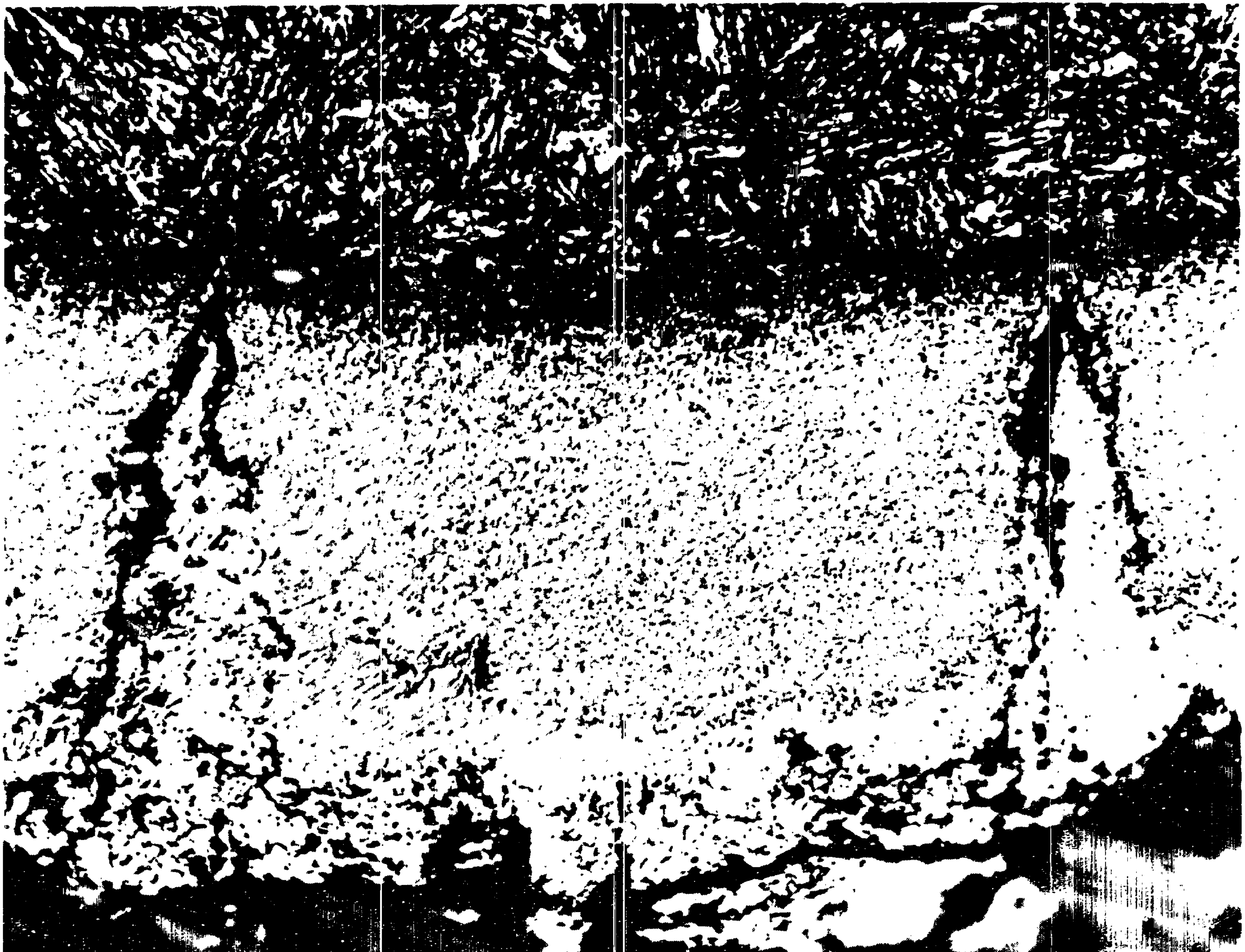


Figure 8. Section thru the top of a land from the development 155 mm XM199 Howitzer after 2706 rounds showing cracks filled with copper alloy in the heat-affected steel (750x) (from Ref. 14).

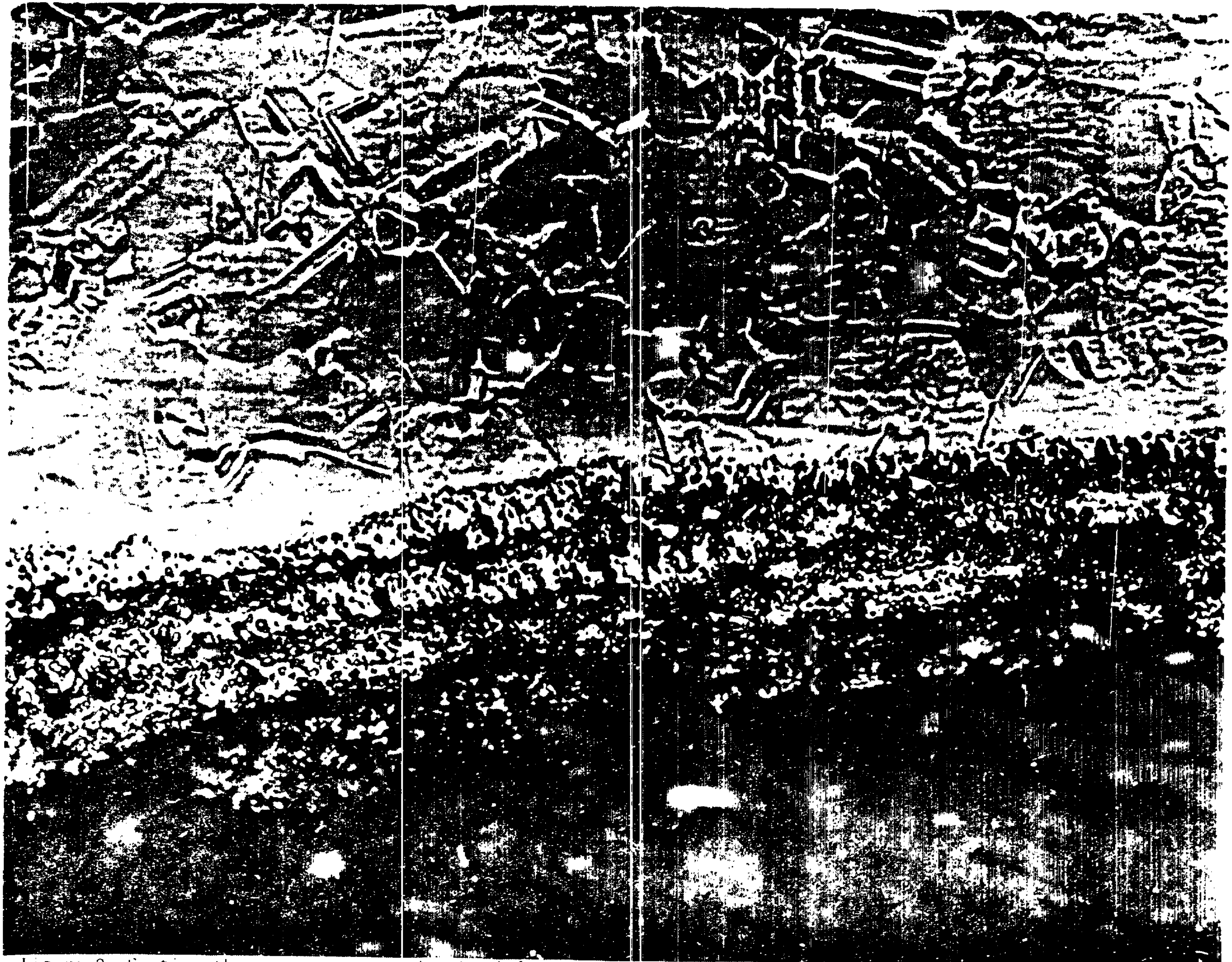


Figure 9. Section thru a copper rotating band from a recovered 8 inch M650 Projectile showing the previously molten surface layer (1000X).

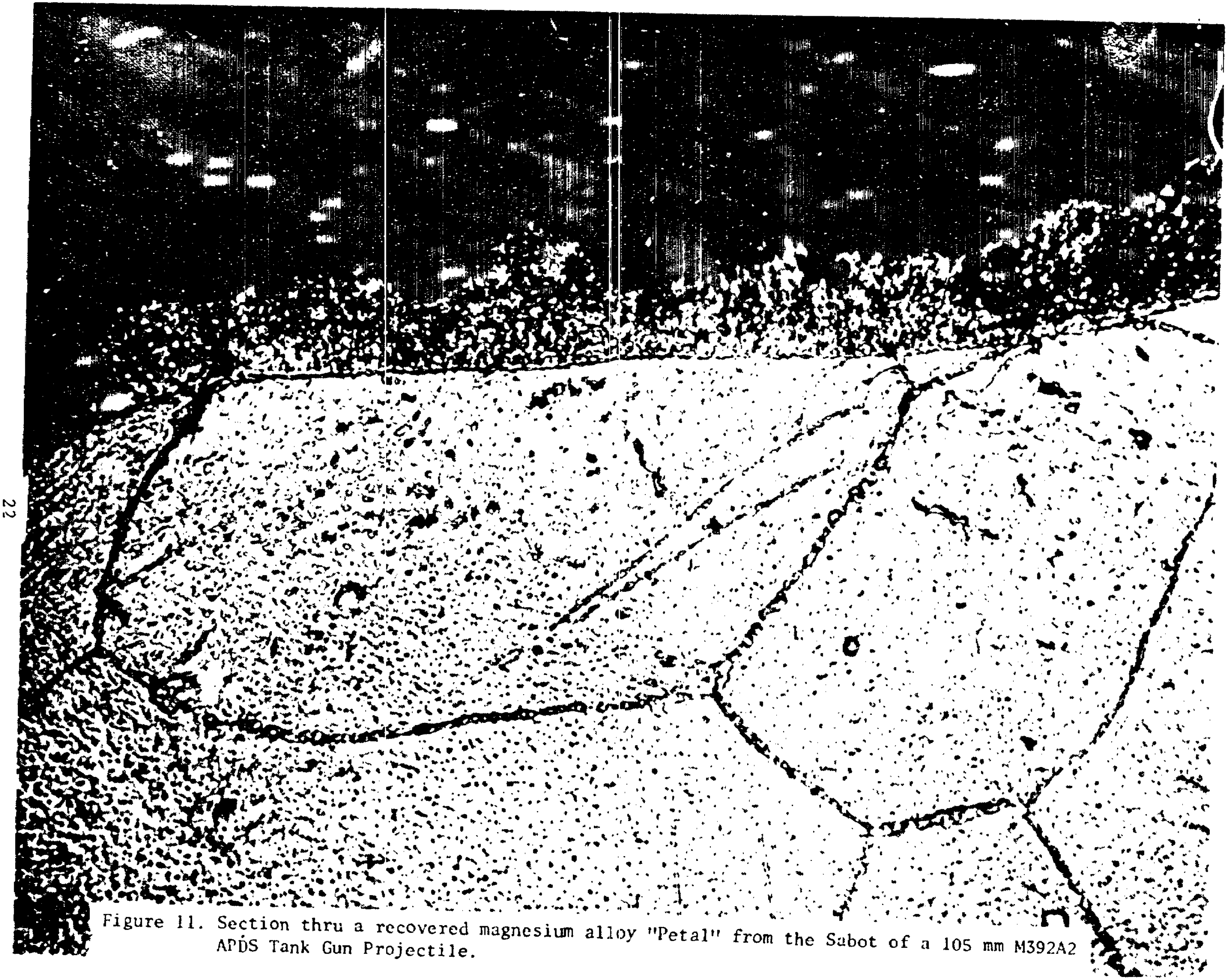


Figure 11. Section thru a recovered magnesium alloy "Petal" from the Sabot of a 105 mm M392A2 APDS Tank Gun Projectile.

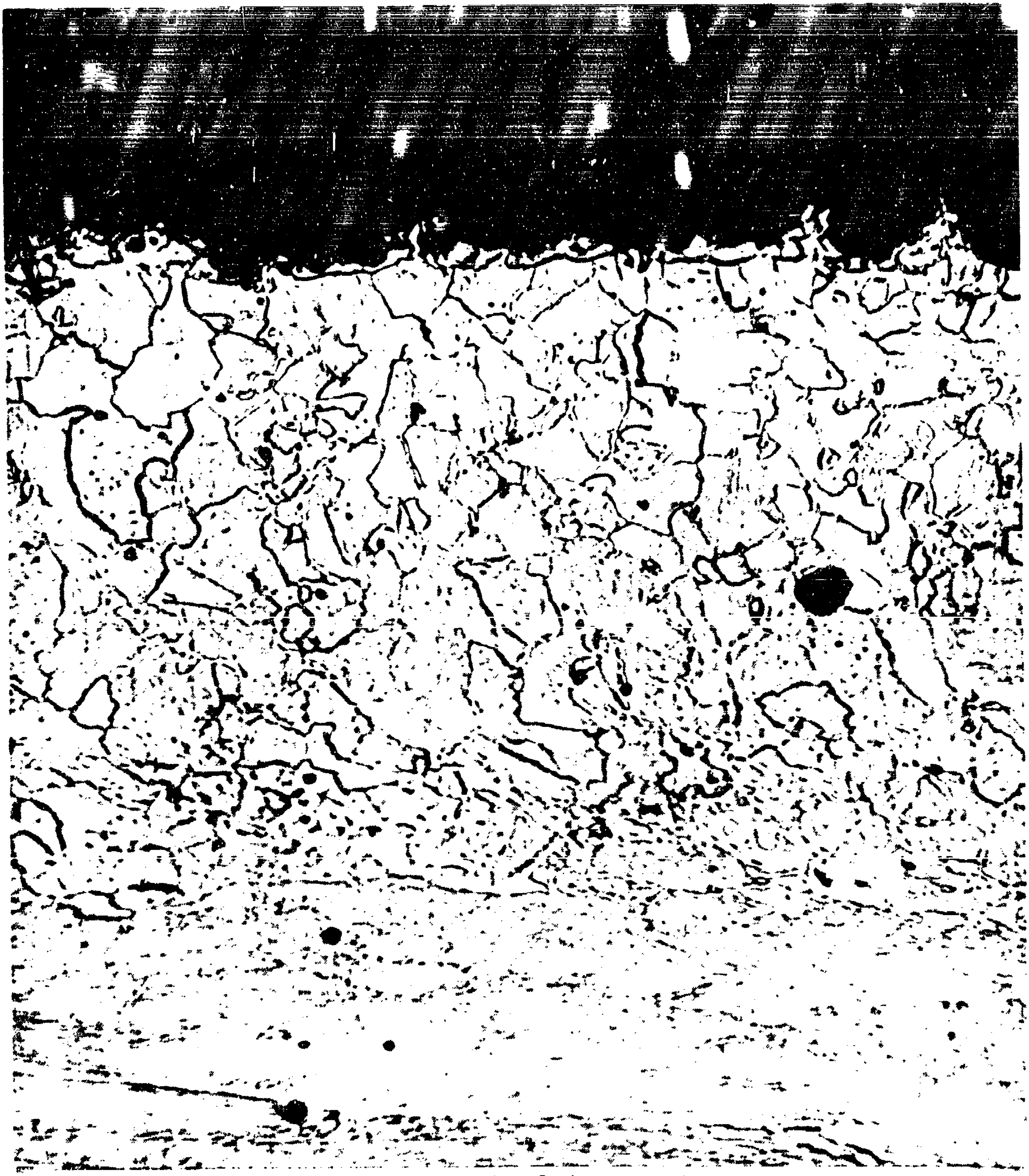


Figure 12. Section thru an experimental soft iron rotating band from a recovered 105 mm M1 Howitzer projectile (1000X).

Figure 13. Section thru body engraving marks on a recovered 8 inch M106 projectile (1000X).

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